Terdiurnal Surface-Pressure Oscillations over the Continental United States

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ABSTRACT

The small terdiurnal pressure oscillation $S_3(p)$ is determined over the conterminous United States by analyzing long time series of hourly barometer data from 180 stations. Spectral analysis of these time series reveals that the terdiurnal band is dominated by three or four spectral peaks, separated in frequency by 1 cpy. The central peak at 3 cpd is invariably smaller than the two immediate side peaks, indicative of extraordinarily strong seasonal variations in the tide. The largest terdiurnal tide occurs over the south-central United States in winter where amplitudes exceed 300 μbar. Summertime amplitudes are roughly one-half as large. Summer and winter tides are almost completely out of phase, with rapid 180° shifts occurring in the equinox seasons when amplitudes are very small.

1. Introduction

The atmosphere displays a variety of thermally and gravitationally driven tidal signals (Chapman and Lindzen 1970). In terms of surface pressure, the two thermal tides at frequencies of once and twice per solar day—denoted $S_1(p)$ and $S_2(p)$—are by far the largest, often of order 1 mbar, and they have understandably attracted the most attention from atmospheric scientists. Yet, as is commonly known, the solar tide has many higher harmonics that are easily resolved above the background noise continuum; Fig. 1 shows a typical spectrum. The tides $S_n(p)$, with periods of $24/n$ h, are clearly evident.

The higher harmonics of the solar barometric tide have only rarely been examined in detail. Chapman and Lindzen (1970) give very brief mention to S_3 and S_4, citing mainly the earlier discussions of Bartels and Kertz (1952) and Kertz (1959), respectively. Butler and Small (1963) have perhaps the most extensive (theoretical) discussion of S_3. Apparently most observational data for S_3 stems from the many old station analyses of Hann, who occasionally determined S_3 parameters simultaneously with the primary S_1 and S_2 (e.g., Hann 1918). For example, the small compilation of Bartels and Kertz (1952) is extracted primarily from Hann's papers.

So there has been an obvious lack of attention to the terdiurnal surface-pressure tide. In contrast, a number of recent papers have addressed S_3 in upper-atmosphere wind data (e.g., Smith and Ortland 2001, and references therein), partly because in some cases the amplitude of the terdiurnal wind tide is found to be comparable to that of the diurnal tide. Part of the motivation for the present study stems from a requirement for very accurate models of high-frequency surface pressures in order to adjust space-geodetic measurements (e.g., Velicogna et al. 2001). For such applications the operational analysis products of national meteorological centers are commonly used. Note, however, that in 6-hourly analysis products the semidiurnal tide occurs at the Nyquist frequency (e.g., Hsu and Hoskins 1989), and so the terdiurnal tide is aliased, or folded, into their reported S_1 signal. Alternative approaches for modeling S_2 and its higher harmonics are therefore desirable.

This paper is devoted to a strictly empirical determination of the terdiurnal $S_3(p)$ tide over the continental, lower-48, United States, a region of sufficiently high

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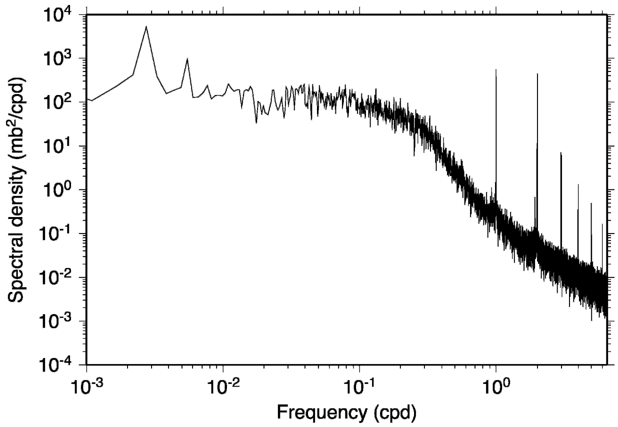

FIG. 1. Spectrum of atmospheric surface pressure at Austin, TX, deduced from a nearly complete time series of hourly barometer measurements from 1976 through 1995. The strong peaks at 1, 2, 3, . . . cpd are the solar atmospheric tides. A small peak near S_2 arising from the gravitational lunar tide (frequency 1.932 cpd) is also apparent.

station density that finer-scale features can be mapped in detail. This paper might therefore be considered an extension of the work by Mass et al. (1991), who empirically mapped the S_1 and S_2 tides over the continental United States, using data from 213 stations. We here use 180 stations, most with considerably longer time spans of data so that the smaller S_3 signal may be reliably estimated.

Figure 2 displays in separate panels high-resolution zoom views of the first three tidal peaks of Fig. 1. One sees that each peak is split into a series of fine lines separated in frequency by 1 cpy, thus representing strong, but highly regular, temporal modulations within each tidal band. One also immediately notices a curious feature of S_3: its central peak is smaller than the two side peaks. This feature is typical of most U.S. stations. It implies unusually pronounced seasonal modulations in S_3, which is consistent with previous studies (Butler and Small 1963) that show much stronger terdiurnal amplitudes during winter months. For this reason, simple annual mean estimates of the terdiurnal tide are an inadequate characterization of the tide and are of less value than annual mean estimates of the S_1 or S_2 tides. A useful analysis of S_3 must explicitly account for its large temporal modulation. Historically this is done by either seasonal or monthly harmonic analyses, but in this paper we prefer to follow the tradition of ocean-tide studies by solving for the amplitudes and phases of each of the spectral lines evident in the terdiurnal band. Once the parameters for each line are known, it is a trivial task to evaluate their summation for any desired time or season.

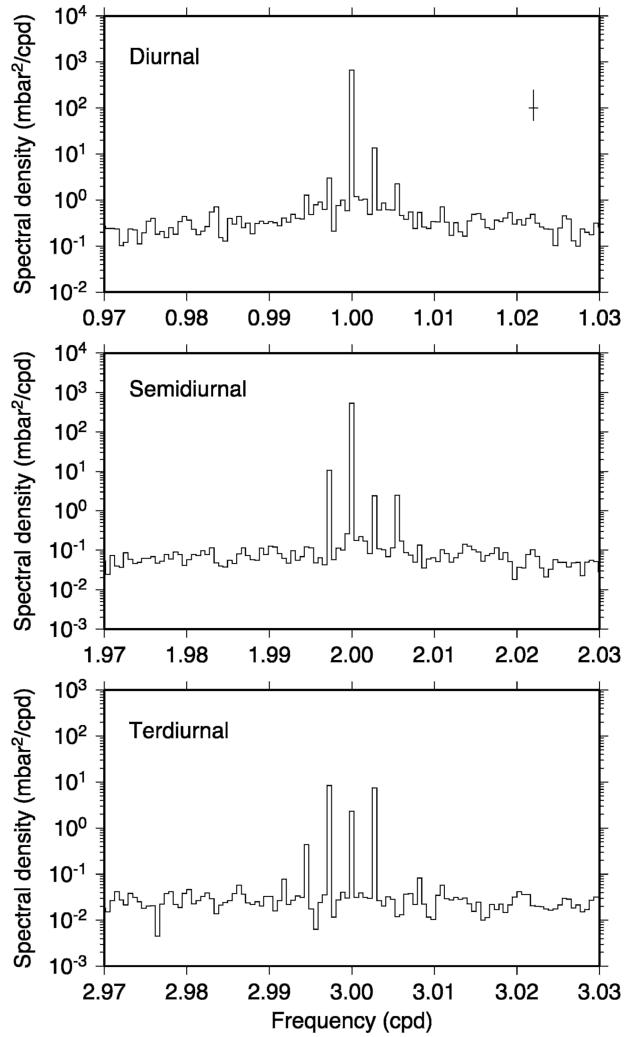

FIG. 2. High-resolution views of the three main tidal peaks seen in the spectrum of Fig. 1. In each panel the primary lines are separated in frequency by 1 cpy. Note that for S_3 the central line is smaller than the two side lines. The spectrum was computed by a combination of Welsh segmenting and frequency smoothing, resulting in 12 degrees of freedom for each spectral estimate.

2. Analysis of station data

All data in this paper are extracted from the data archives of the National Center for Atmospheric Research (NCAR), and specifically from their database denoted DS470. In the main these data correspond to database TD3280 at the National Climatic Data Center in Asheville, North Carolina. The data are (predominantly) hourly measurements from meteorological stations located at airports within the United States and at a handful of other locations. The earliest data are from 1940; the latest data in our analysis are through 2000. Only surface-pressure measurements are used in this analysis; as Mass et al. (1991) have convincingly shown,

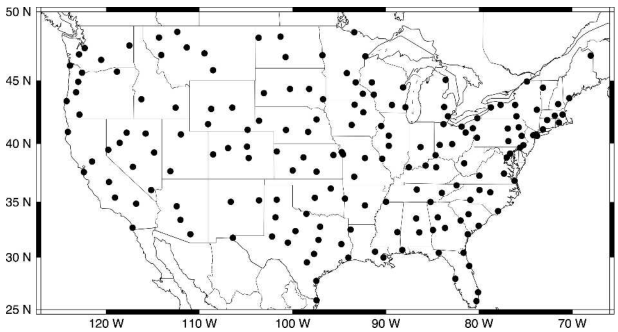

FIG. 3. Locations of stations.

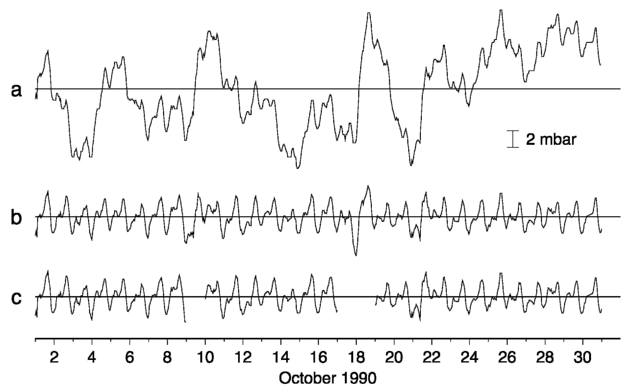

FIG. 4. Processed barometric pressure time series from Austin during Oct 1990: (a) original data, (b) high-pass-filtered data, and (c) data after undergoing automatic editing for remaining "nontidal" variability.

tidal estimates from data that have been reduced to sea level are corrupted by the methods used for such reductions.[1]

Because the terdiurnal tide is a relatively small signal, we implemented a number of special data processing and quality control procedures to improve the robustness of the tidal estimates. These are described presently. In addition we use only long, multiyear time series in order to benefit from the reduction in estimation error that comes with large sample sizes as well as to smooth out any real interannual variations in the tide [which, of course, are of keen interest in their own right (e.g., Vial et al. 1994) but are not the topic of primary concern here]. The shortest time series we accepted consists of 12 full calendar years. The longest is 55 yr. The median is 33 yr. Station locations are shown in Fig. 3.

One of the most useful quality checks is to estimate the tides for each individual year of a multiyear time series and to monitor the consistency of the resulting estimates (allowing, of course, for the possibility of true interannual variability). Such comparisons can highlight spurious data as well as provide credible uncertainty estimates on the tidal estimations. Examination of yearly tidal phases, especially for the larger tide S_2, can easily pinpoint timing errors; a 30-min timing error, for example, will shift the estimated phase of S_2 by 15°. We used this method to confirm (as noted in the TD3280 documentation) a 30-min shift in data-recording times in June 1957 (i.e., earlier data were recorded at half past the hour although the listed times are given only on the integer hour). In addition, we noticed a shift of about 1 h in the yearly estimated S_2 phases for 1942 through 1944 and somewhat less for 1945. This is almost certainly a timekeeping artifact brought about by the American government's adoption during World War II of continuous daylight saving time, then called "War Time," which was used from 9 February 1942 through 29 September 1945. We have therefore corrected the times of all our data in this interval by 1 h.

More accurate tidal estimates are also obtained by removing from the data as much of the nontidal variability as possible. As can be seen from the example in Fig. 4, a high-pass filter removes all power below the diurnal band but leaves some high-frequency contamination associated with the peaks and troughs of synoptic weather systems. To attempt to remove these we have deleted data based on the residual daily variance after high-pass filtering (the entire 24 h of suspect days are removed to prevent any possible phase bias). The number of days removed rests on the following idea: Outliers, including those associated with rapidly moving fronts, tend to produce an observed pressure distribution with positive kurtosis (i.e., leptokurtic, or peaked with heavy tails), while a pure tidal signal will have a distribution with negative kurtosis (i.e., platykurtic, or flat relative to the normal distribution)—see Walden and Prescott (1983). Removal of days with highest residual variances lowers the kurtosis, and the procedure is to do this until the kurtosis drops well negative: at least below -0.1. In no case, however, do we allow removal of more than 5% of the data. While the procedure is not foolproof—notice in Fig. 4 the still-remaining contamination near the beginning of day 21—much of the nontidal contamination is eliminated.

Each of the filtered and edited time series from the 180 stations was subsequently subjected to least squares harmonic tidal analysis for a set of discrete frequencies, a well-understood practice in ocean-tide and earth-tide studies but somewhat unusual in air-tide studies [an

[1] It is unfortunate that some data centers archive only "reduced" sea level pressures and not the original station pressures.

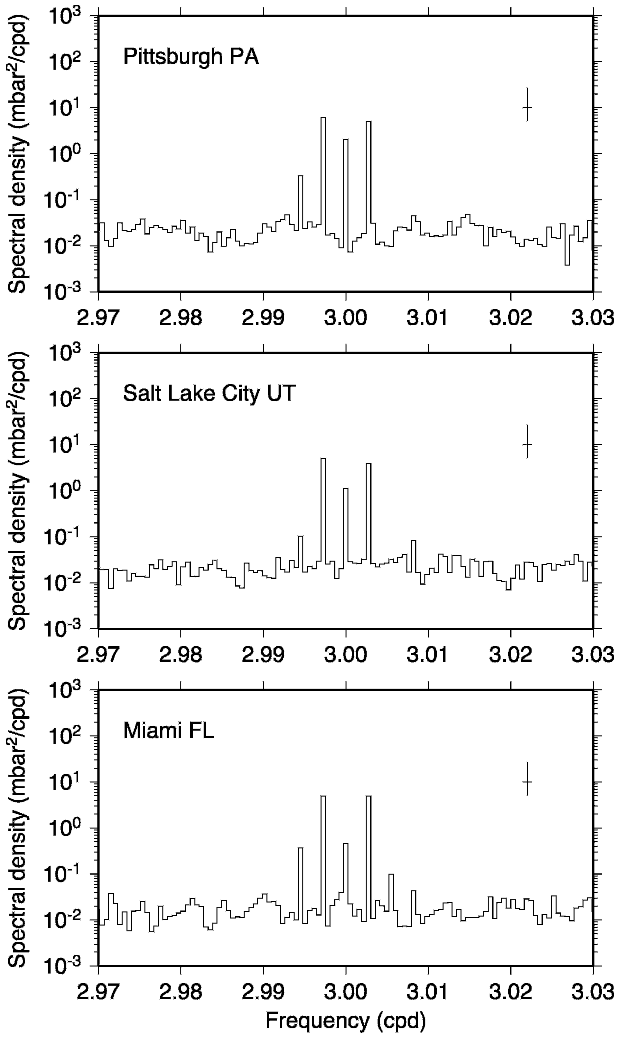

FIG. 5. High-resolution estimates of the air-pressure spectrum within the terdiurnal band for Pittsburgh, PA; Salt Lake City, UT; and Miami, FL. As in Fig. 2 all spectral estimates are based on nearly complete 20-yr time series of hourly surface pressures.

exception is Chapman and Malin (1970)]. The procedure is clearly useful when the tidal band is dominated by a few spectral lines, as is here the case; it would be less useful if the central tidal peak were surrounded by a large "cusp" of stochastic energy, which in our experience is more likely to occur around the S_1 line than around S_3.

Tidal analysis

The appearance of four main spectral lines within the terdiurnal band, as evident in Fig. 2 for data from Austin, Texas, is typical of most U.S. stations. Figure 5 shows three further examples. Additional small lines are occasionally evident (e.g., at Miami, Florida, where six lines can be seen), but in general only four lines are clearly above background noise. The goal of a terdiurnal tidal analysis is thus to determine for each barometer station the amplitudes and phases of these four major lines. Lacking any well-established terminology, we refer to these tidal lines, or "constituents," as U_3, T_3, S_3, and R_3, from lowest to highest frequency. Such nomenclature loosely imitates Kelvin's standard terminology for the semidiurnal ocean tide, for which he appropriated the two closest letters in the alphabet, R_2 and T_2, to denote the two elliptic modulation tides that differ in frequency by 1 cpy from the central S_2 (Cartwright 1999).

We take the tidal arguments as in Table 1, where t is

TABLE 1. Terdiurnal tidal constituents [a fifth constituent at $(3t + 2h)$ is generally very small at U.S. stations].

	Argument	Frequency ($^\circ$ h^{-1})
U_3	$3t - 2h$	44.917 86
T_3	$3t - h$	44.958 93
S_3	$3t$	45.000 00
R_3	$3t + h$	45.041 07

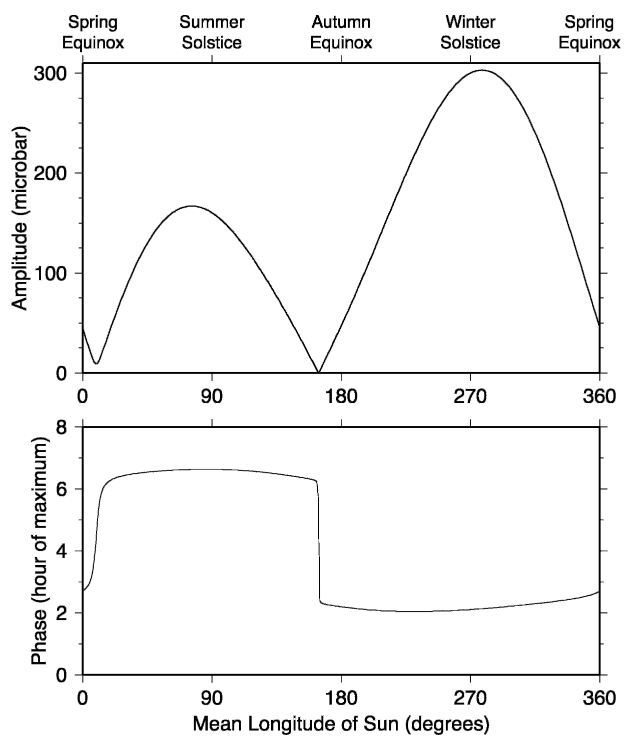

FIG. 6. Time-varying (top) amplitude and (bottom) phase of the terdiurnal tide at Austin as a function of the mean solar longitude h, based on a combination of four terdiurnal tidal constituents. Phase is shown in terms of the local time in hours (modulo 8) at which high pressure occurs.

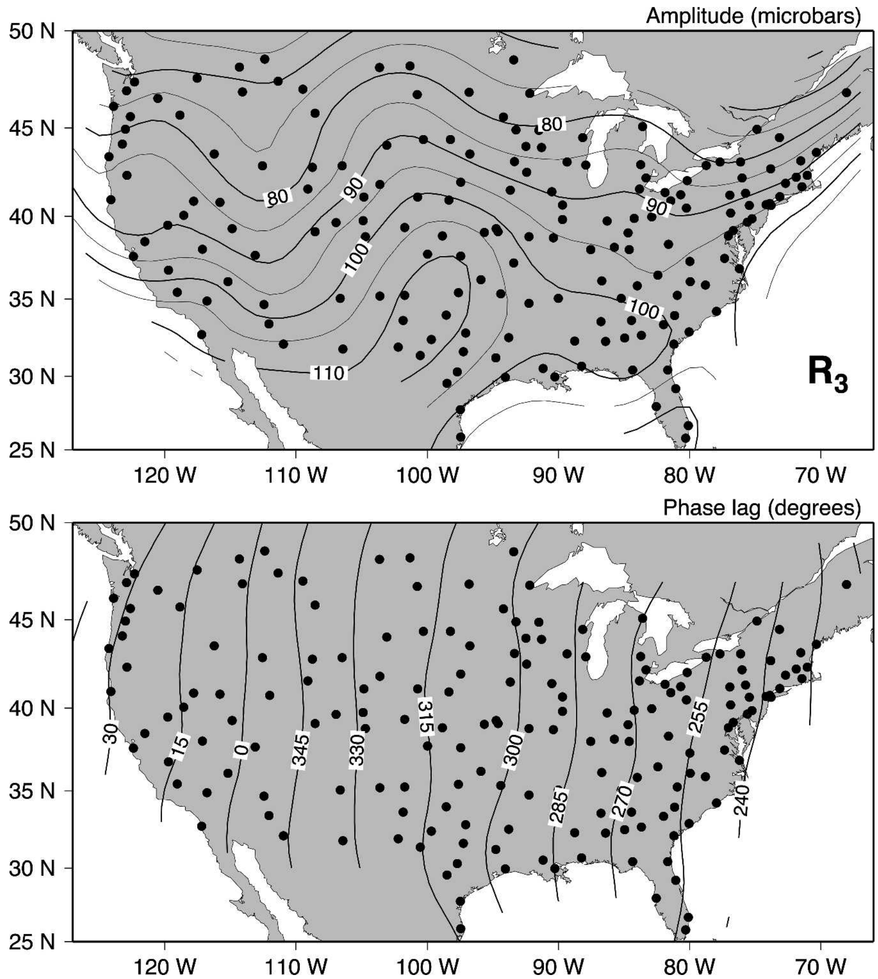

FIG. 7. (top) Amplitude and (bottom) phase of the terdiurnal tidal constituent R_3. Phases are Greenwich phase lags relative to the argument given in Table 1.

universal time and h is the mean longitude of the sun, reckoned as usual with respect to the vernal equinox. As h varies by 360° in one year, its presence in the arguments as given by Table 1 effects the required 1-cpy frequency offset between the spectral lines of the tidal band. A formula for h sufficiently accurate for the late twentieth and early twenty-first centuries is (Meeus 1998)

$$h = 280.466° + 0.985647T_d,$$

where T_d is the number of days since 1200 UTC 1 January 2000.

Let $\theta(t)$ stand for any of the listed arguments of Table 1. The corresponding tidal oscillation is expressed as $A \cos[\theta(t) - G]$, with amplitude A and Greenwich phase lag G. Conversion of phase lags from Greenwich time to local time is trivial: local phase $g = G + \omega\lambda/15$, where λ is station longitude in degrees, positive east of Greenwich, and ω is the tidal frequency in degrees per hour, as in Table 1. We use both phases G and g below.

The eight terdiurnal parameters were estimated at each station by least squares from the entire available multiyear time series of filtered pressures. Simultaneously we also estimated tidal parameters within the diurnal and semidiurnal bands, but these results are irrelevant to the present subject and are not discussed. Standard errors were estimated in two ways: from the standard deviation of yearly (subset) estimates scaled by $k^{-1/2}$ for k years of the entire time series and from the least squares covariance matrix scaled by the spectral noise background near the terdiurnal band. These two error estimates usually turned out to be very consistent, nearly always well within a factor of 2.

As an example solution, consider again the Austin time series. The estimated tidal parameters A and G, based on 35 yr of hourly data, are (27 μbar, 155°), (117

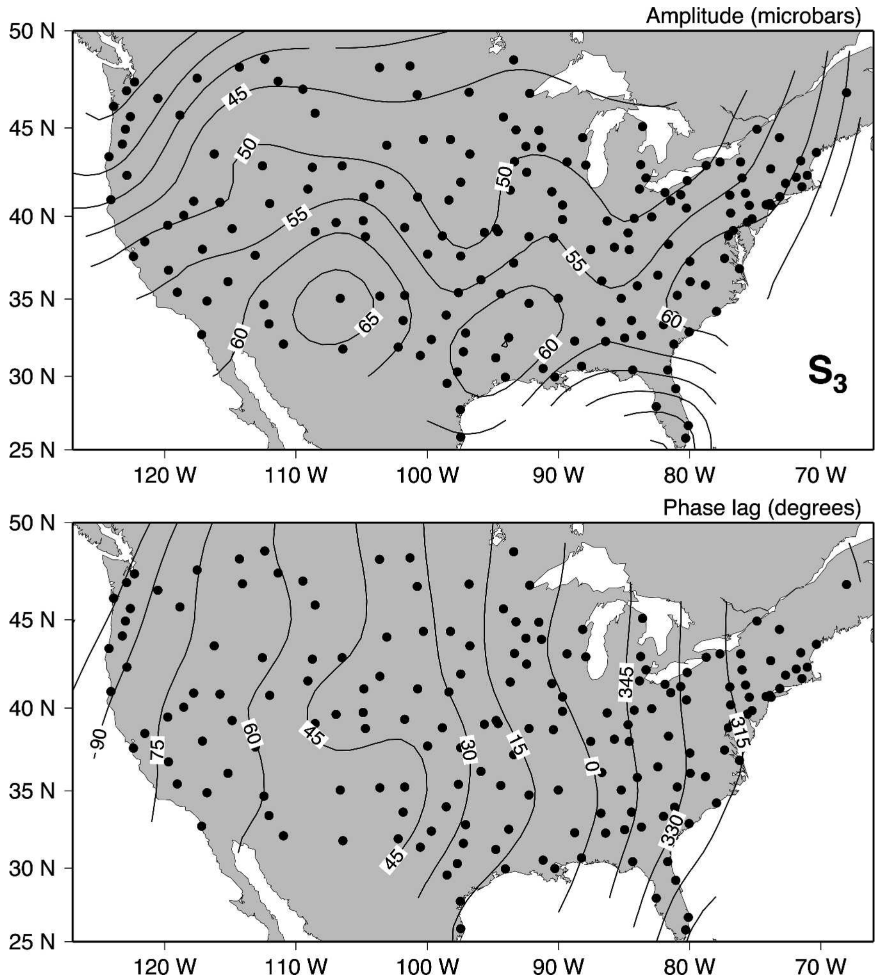

FIG. 8. As in Fig. 7, but for the terdiurnal tidal constituent S_3.

μbar, 127°), (61 μbar, 18°), (108 μbar, 306°), for the tides U_3, T_3, S_3, and R_3, respectively. Standard errors for all four constituents are about 2 μbar. In agreement with Fig. 2 the amplitude of the central constituent S_3 is approximately one-half that of the nearest two side lines. With estimates of these four tides in hand, their summation may be evaluated for any time t. It is also straightforward to evaluate an implied time-varying terdiurnal amplitude and phase as a function of the solar longitude h. This is an exercise in simple trigonometry—combining four sinusoids into a single one of varying amplitude and phase—and the interesting result for Austin is shown in Fig. 6. [The phase in this figure has been converted to local time ($\lambda = -97.7°$ for Austin) and displayed as the time of maximum pressure.] Evidently the terdiurnal tide at Austin is maximum during winter and summer and relatively weak during the equinox seasons, at which times the phase abruptly changes by 180° (or 4 h). Between the two equinoxes the phase remains relatively constant. The occurrence of peak amplitudes during winter is consistent with the observed times of peak amplitudes of terdiurnal thermospheric winds (e.g., Thayaparan 1997; Smith and Ortland 2001; Akmaev 2001).

3. Cotidal charts

The main results of this analysis are shown in Figs. 7–10 in which the amplitudes A and Greenwich phase lags G are displayed for the continental United States. These charts were computed by simple statistical interpolation (Daley 1991, section 4.2) of the 180 station tidal estimates. For each tide a biquadratic polynomial was used to generate a background field to partially account for the obvious trends in the maps, and the resulting residuals were assumed to satisfy an isotropic correlation model with a decay scale of 500 km, which is roughly consistent with the correlation computed directly from the data. Analysis of the interpolation residuals indicated four stations having unacceptably

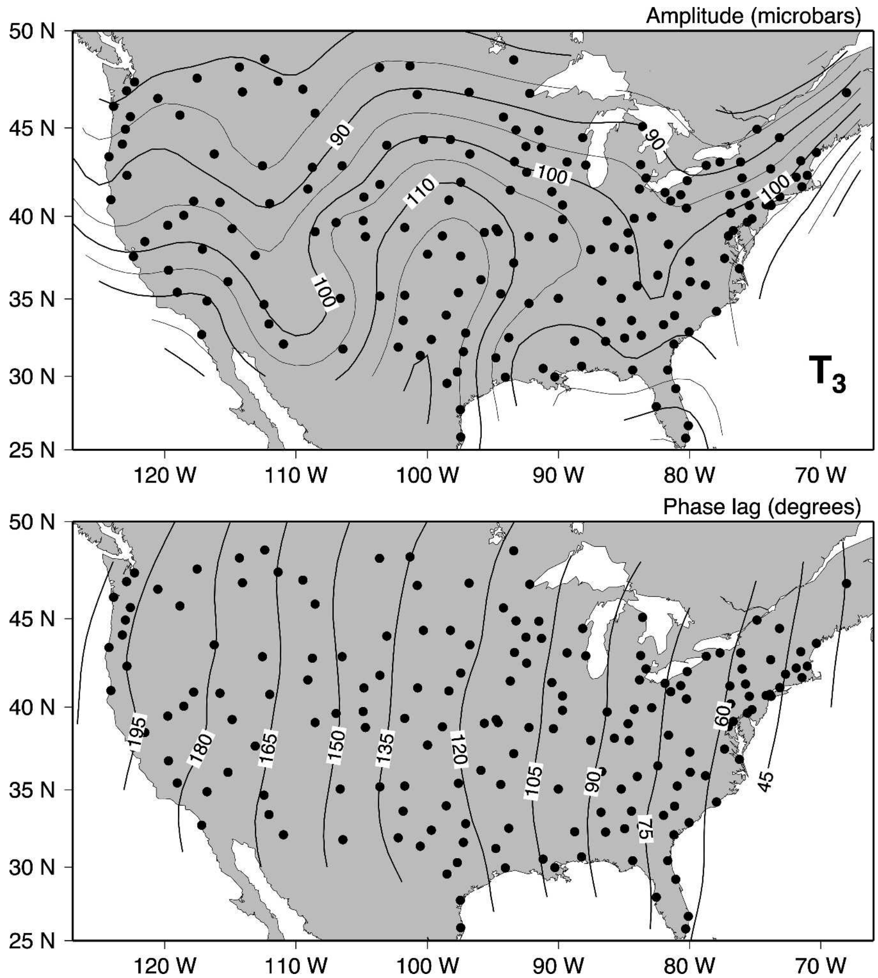

FIG. 9. As in Fig. 7, but for the terdiurnal tidal constituent T_3.

large outliers; these stations (Meridian, Mississippi; El Paso, Texas; Evansville, Indiana; Springfield, Illinois) all differed from the interpolated fields by approximately 45° in phase, an offset that most likely arises from an error in time zone. These four station phases were thus adjusted by precisely 45°, yielding the final interpolated tidal charts in Figs. 7–10.

The root-mean-square residuals of the station tide estimates relative to the interpolated fields are 3.3, 5.2, 3.6, and 2.2 μbar for the R_3, S_3, T_3, and U_3 constituents, respectively. These values are only slightly larger than the estimated standard errors of the station estimates themselves. The rms of S_3 is curiously inflated relative to the larger tides, but no obvious reason for this is evident.

Excepting the four time-zone errors, the largest residual arises from the station at Eagle, Colorado (39°39′N, 106°55′W). The estimated amplitude of T_3 at Eagle is 127 $\pm$ 2 μbar, which is about 22 μbar larger than the interpolated amplitude in Fig. 9. In fact, this T_3 amplitude is the largest terdiurnal amplitude in the entire 180-station dataset. Eagle station, at 2014 m above sea level, is also the highest-elevation station. Whether these two facts are related, we cannot say from the present data in hand; an analysis of additional high-elevation station data would be of interest.

Figures 7–10 have many similarities and a few interesting differences. The three largest constituents are seen to have largest amplitudes in the south-central part of the continent, roughly similar to the region of peak amplitudes of the diurnal tide (Mass et al. 1991). Like the diurnal tide, the terdiurnal tide is significantly less zonal than the semidiurnal tide. The small U_3 constituent attains peak amplitude over Georgia. All four constituents decay southward across Florida.

The Greenwich phases of the two primary constituents R_3 and T_3 show a relatively uniform westward march of the pressure wave across the entire region. (Greenwich phase lags increase in the direction of propagation.) In contrast, the smaller constituents show

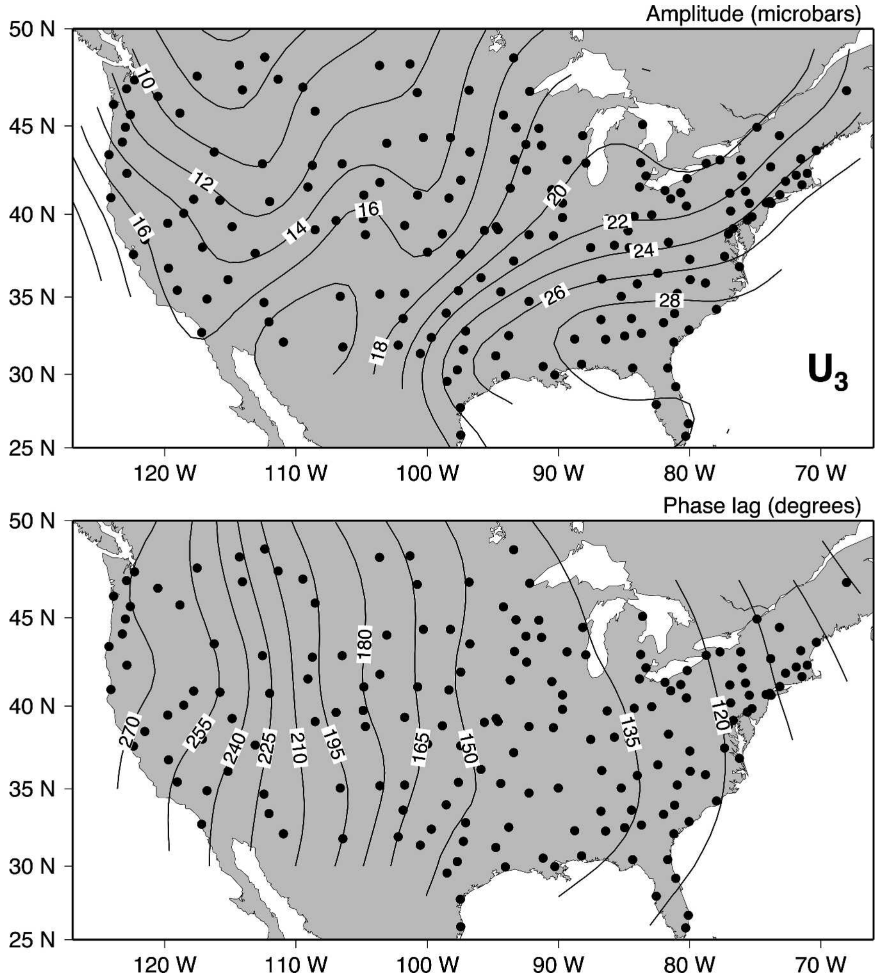

FIG. 10. As in Fig. 7, but for the terdiurnal tidal constituent U_3.

a less uniform phase speed, with U_3 being far more rapid in the eastern United States.

Figure 11 shows the instantaneous terdiurnal amplitudes across the continental United States for the four seasons at which the solar longitude is equal to 0°, 90°, 180°, and 270°. The figure emphasizes the striking seasonal dependence, with winter amplitudes almost 2 times those in summer, and with very small amplitudes when the sun is near the equator. Local terdiurnal phases are not shown but they agree well with those shown for Austin in Fig. 6. During winter the terdiurnal tide peaks near 0630 (modulo 8) local time across the entire region. During summer the tide peaks between 0130 and 0230.

4. Summary

As seen in high-resolution spectra of surface pressure (Figs. 2 and 5) the terdiurnal tide over the continental United States consists primarily of a small set of discrete spectral lines, separated in frequency by 1 cpy. The central line at frequency exactly 3 cpd is invariably smaller than the nearby side lines, which is unlike the diurnal and semidiurnal tides for which the central line always dominates. This indicates extraordinarily large temporal variations of the terdiurnal tide over the course of a year. Largest terdiurnal amplitudes occur near the time of winter solstice, with midcontinent amplitudes then exceeding 300 μbar, a significant fraction of the total daily pressure oscillation (Mass et al. 1991).

The main analysis results of this paper appear in Figs. 7–10, which show the amplitudes and phases of the four primary spectral components of the terdiurnal tide. In conjunction with the tidal arguments of Table 1, the presented cotidal charts allow straightforward evaluation of the terdiurnal pressure oscillation at any given time, continuously throughout the year.

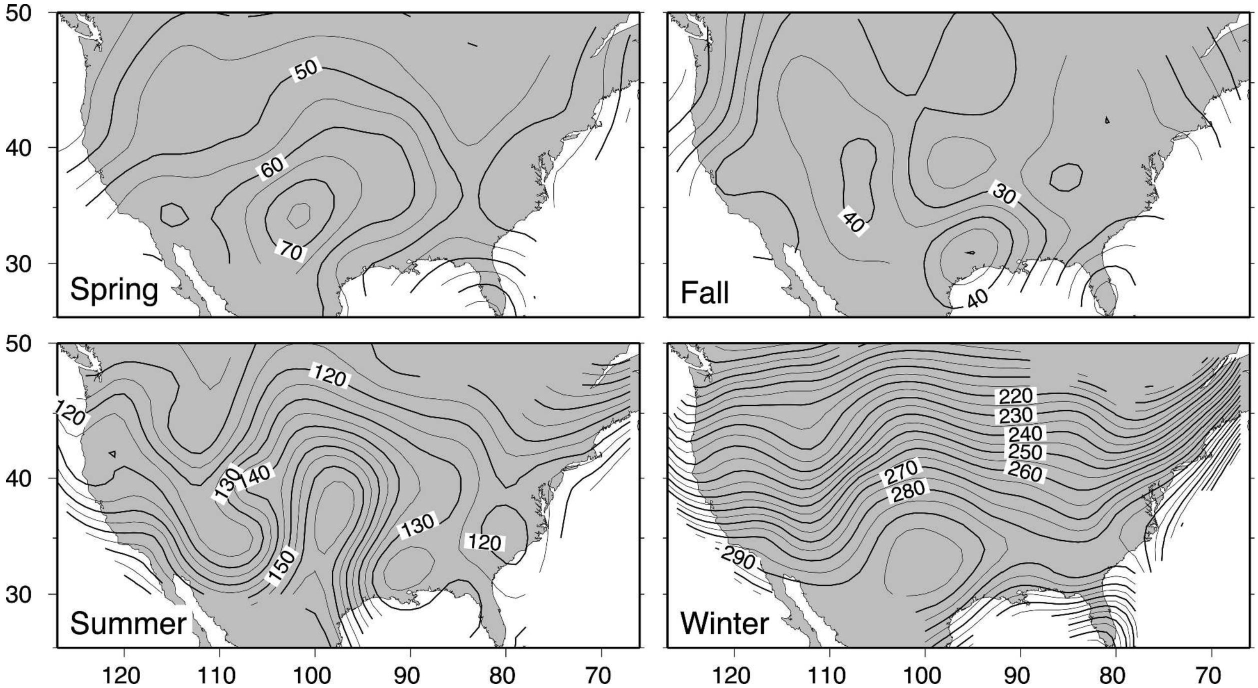

FIG. 11. Instantaneous amplitudes (μbar) of the terdiurnal tide based on the four harmonic constituents R_3, S_3, T_3, and U_3 shown in Figs. 7–10, evaluated for each season. Corresponding (local) phases are nearly constant during each season and agree approximately with those shown for Austin in Fig. 6.

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